

# Bioavailability of Heavy Metals Using Simultaneously Extracted Metal/Acid Volatile Sulfide in the Sediments of Lake Burratorang, NSW, Australia

Archana Saily Painuly<sup>1,\*</sup>, Surendra Shrestha<sup>2</sup>, Paul Hackney<sup>3</sup>

<sup>1</sup>Faculty of Chemical Sciences, Shri Ramswaroop Memorial University, Lucknow, India

<sup>2</sup>School of Computing, Engineering and Mathematics, University of Western Sydney, Sydney, Australia

<sup>3</sup>Parramatta City Council, Sydney, Australia

\*Corresponding author: [archana.cy@srmu.ac.in](mailto:archana.cy@srmu.ac.in)

Received January 08, 2015; Revised January 20, 2015; Accepted January 29, 2015

**Abstract** Lake Burratorang in the south west of Sydney is one of the largest domestic water supply storages in the world, holding 2,057,000 million liters of water. The reservoir provides approximately 80% of water for a population of about 4 million people. To ensure that the best quality water is delivered to Sydney residents the sediment of Lake Burratorang was analyzed for heavy metals as the cause of contamination could be the resuspension of settled material during major inflow events. This study was aimed to evaluate the distribution of heavy metals and their speciation in sediments of Lake Burratorang to predict their bioavailability to the aquatic system. Sediment core samples from Lake Burratorang were subjected to speciation using simultaneously extracted metal (SEM) and acid volatile sulfide (AVS) ratio to determine the potential toxicity of sediments due to metals. The results showed that these SEMs at all stations were higher than AVS and their ratio was found greater than 1, which indicates that available AVS is not sufficient to bind with the extracted metals for Lake Burratorang sediments and possibly contained metals potentially bioavailable to benthic organisms, however, SEM/AVS ratio was high owing to relatively low AVS values compared to values reported in the literature for fresh water sediments and not due to high concentrations of metals. In the current study even though these investigated metals were bioavailable in the sediment their individual metal concentrations are not expected to be toxic to benthic organisms as all locations had SEM concentrations lower than their threshold effect level (TEL). However, the slight increase in SEM above TEL will be detrimental for aquatic system as available AVS in sediment of Lake Burratorang is not sufficient to bind with the extracted metals.

**Keywords:** anoxic sediment, acid volatile sulfide, simultaneously extracted metal, heavy metals

**Cite This Article:** Archana Saily Painuly, Surendra Shrestha, and Paul Hackney, "Bioavailability of Heavy Metals Using Simultaneously Extracted Metal/Acid Volatile Sulfide in the Sediments of Lake Burratorang, NSW, Australia." *Journal of Environment Pollution and Human Health*, vol. 3, no. 1 (2015): 12-17. doi: 10.12691/jephh-3-1-3.

## 1. Introduction

Lake Burratorang in the south west of Sydney, Australia, is one of the largest domestic water supply storages in the world, holding 2,057,000 million liters of water. The Lake is located within the Greater Blue Mountains Area World Heritage Site. The Lake acts as a final contaminant removal area, before the water is piped to the Prospect Water filtration plant in Sydney.

The Lake, is fed by several major rivers (Figure 1). The catchments of these rivers have differing geological, topographic and land use characteristics, which result in contributions of varying water quality to Lake Burratorang. The major pollution sources identified during the catchment audit process by the Sydney Catchment Authority (SCA) are extensive agriculture, mining, sewage systems, transport related, chemical,

ceramics and other industries. The quality of water within the Lake came under scrutiny after pathogens *Cryptosporidium* and *Giardia* were detected in the treated drinking water leading to Sydney's "Boil Water Crisis" in 1998.

In spite of the significance of Lake Burratorang to a large population of the Sydney, no systematic metal distribution and speciation study of its sediments had been carried out in the past. This study examined the spatial distribution of AVS and SEM in the sediments of the Lake Burratorang in order to elucidate the influence of catchment activities on AVS and SEM distribution and assess the potential toxicity of heavy metals.

Sediments are an integral component of aquatic ecosystems. On one hand it promotes self purification of aquatic environment because of depositing pollutants, but under certain conditions the bottom sediments can be a strong source of secondary water pollution. Sediment analysis has become the focus of study for the last two -

three decades. Within sediments, heavy metals pollution is a major concern due to their toxicity and ability to accumulate in the biota. In oxic sediments, the most important phases in metals are those containing hydrous iron and manganese oxides [1]. In anoxic sediments, sulfide phases dominate and the bioavailability of heavy metals is largely controlled by the absorption and coprecipitation of the metals with sulfide minerals [2,3,4,5]. In the late nineties, the acid volatile sulfide (AVS) concept has been introduced in a number of risk assessment studies of anaerobic, heavy metal-polluted freshwater sediments [6,7].

Acid-volatile sulfide (AVS) is operationally defined as those sediment sulfides that are soluble in hydrochloric acid [8]. AVS, comprising essentially iron monosulfides in sediments, are available for binding divalent cationic metals through the formation of insoluble metal-sulfide complexes [4,9,10], thereby controlling the metal bioavailability and subsequent toxicity for benthic biocommunities. The AVS-bound metals, with environmental concern (usually Cd, Cu, Ni, Pb and Zn), are extracted at the same time and are called simultaneously extracted metals (SEM). The ratio or the difference between AVS and SEM gives an indication of the potential sediment toxicity.

In light of the importance of the AVS- SEM concept for assessing the ecological risk of metals in sediments it was considered necessary to evaluate the bioavailability of heavy metals in Lake Burragorang sediments and determine if there is any relationship between human land use pattern and AVS-SEM values. There is a lack of information with respect to levels of SEM and AVS in marine and freshwater sediments of Australia.

## 2. Materials and Methods

### 2.1. Study Area and Sample Pretreatment

Recommendations of [11] have been followed in this study for sample collection, handling and storage. Four cores in duplicates (Figure 1) were collected during November 2005 for AVS-SEM study (a) Site DWA2 (300 m upstream of Dam wall): This is an important location as most of the water is extracted near this point and supplied to Sydney Water, (b) DWA18: It is located at the inflow site of the Cox and Kedumba River (36 km upstream), (c) DWA27: It is located in the middle of Lake and (d) DWA35: It is at the inflow site of the Nattai river. Sediment cores were collected using KB messenger-operated gravity type core sampler. The sediment core enabled sediment cores up to 45cm in length and 4.3cm in diameter. Each sediment cores were sliced at 5 cm interval throughout the entire length using sediment core extrusion device. All sediment samples were wet sieved through 63  $\mu$ m nylon mesh screen and homogenized.

### 2.2. Sample Analysis

Analyses of AVS and SEM concentrations in sediments, followed the cold-acid purge-and-trap method of [9] Allen et al. (1993) and were conducted within one week of sample collection. All AVS determination was performed in nitrogen gas filled glove box. Simultaneously extracted metals (SEM) were extracted in 1M HCl [5] for 30 min at

room temperature. Metal concentrations in all solutions were determined using ICP-AES and ICP-MS. The moisture content was determined by measuring the weight loss after drying at 105°C for 24 h. The pH value was measured in a 1:5 solid: liquid (deionised water) suspension. The content of total organic matter and carbonate was estimated according to the loss on ignition [12]. The analytical procedure for the determination of acid extractable metal concentrations was checked by means of analysis of standard reference samples- AGAL-10 (reference sediments from Hawkesbury River, NSW) and AGAL-12 (biosoil, a mixture of soil and dried sewage sludge). These reference samples were obtained from the Australian Government Analytical Laboratories (Pymble, NSW). The observed values obtained were within, or close to certified values. The percentage recovery for all metals ranged between 75% and 107%.

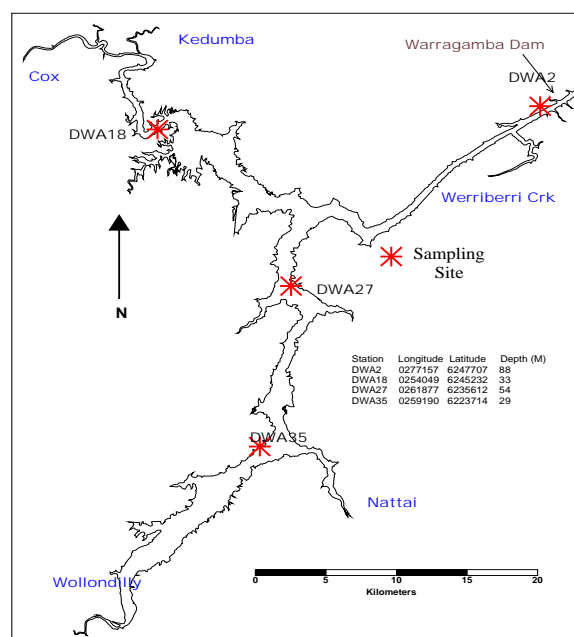


Figure 1. Lake Burragorang showing sampling locations

The different results reported and discussed are the average of minimum of two determinations. Blank determinations were carried out wherever necessary and the corrections were made if required. During the analysis for different parameters blanks, duplicates, spikes and standards were processed on 5% basis. The percentage recovery of spiked samples in metal determinations ranged from 94 to 104%, which indicate that the results are accurate and unbiased. Relative percent difference of duplicate measurements was less than 10%, which is a satisfactory precision. The relationships among different variables were determined by calculating Pearson's coefficient of correlation. All statistical analyses were carried out using statistical software SPSS version 17.0 for Windows.

## 3. Results and Discussion

### 3.1. Spatial and Vertical Distribution of Physico-Chemical Parameters

The physical-chemical parameters of sediment cores are shown in Table 1. Sediment pH value ranged from 6.0 to

7.8 represented slightly basic to neutral to slightly acidic nature. Highest pH viz. basic nature was observed in core DWA 18. Organic matter in sediments mainly derives from phytoplankton, zooplankton and other organic materials. Organic matter decreases with depth at sites DWA27 and DWA2 (near dam wall). Interestingly down towards the Cox river in north (DWA18) organic percentage became relatively constant while going down. At DWA35 similar trend was observed for organic percentage, however, two peaks found at 10 and 25 cm layers. The organic matter values are not very high (10% to 12%) except at DWA2 at a depth of 35 cm (21.4%). The values between 12 and 14 are indicators of the allochthonous origin of organic matter [13]. The percentage of carbonate contents were more or less constant with a slight decrease at the bottom at all sites except DWA35. In general, low carbonate content in sediments (<10%) is attributed to terrigenous materials transported from catchment and near catchment area by winds, floods and waves [14].

### 3.2. Spatial and Vertical Distribution of Acid Volatile Sulfide

The distribution of AVS with depth in sediment cores are presented in Table 2 and Figure 2. Sediment samples at all sites and depth contained AVS concentrations above the lower limit (0.01  $\mu\text{mol/g}$ ) [9]. The highest sulfide levels were obtained from site DWA2 (range from 0.59 to 0.12  $\mu\text{mol/g}$ ), while lowest levels were obtained from site DWA35 (range from 0.25 to 0.09  $\mu\text{mol/g}$ ). AVS concentration at all four sites was low at the surface (5 cm) compare to intermediate depths. Two peaks of AVS were found at 10 and 20 cm layers in cores from DWA2 (near dam wall) and at 10 and 25 cm in core DWA27 and DWA35. In core DWA18, two peaks at 15 cm and 25 cm were identified. From the above distribution patterns, it

appears that the AVS contents generally decrease along the profile with peaks at various depths. These profiles of AVS indicated non-steady deposition processes with instabilities during deposition [15]. These results are consistent with the findings of other studies indicated that surficial concentrations of AVS were smaller than those in deeper sediments [8,16-21].

The factors affecting the AVS contents in sediment are organic matter, the rate of sulfate reduction and redox status of sediments [22]. There were no correlation exist between AVS and organic matter at all locations (Table 3). So, organic matter may not be major controlling factor for AVS content. Relatively high Eh at surficial sediment [23] and downward diffusion of  $\text{O}_2$  to several centimeters of the sediment–water interface cause the depletion of AVS by oxidation [24]. Therefore, the AVS content was very low in the top 5–10 cm of the sediment cores. Below this depth the peaks of AVS content in the profiles may be due to lower Eh, increased sulfate bacterial activity [25] and sudden change in depositional conditions [26]. At greater depth, the activities of sulfate reducing bacteria would decrease and AVS become reduced to  $\text{FeS}_2$ , therefore, AVS concentration decreased gradually with the sediment depth [8].

### 3.3. Spatial and Vertical Distribution of Simultaneously Extracted Metal

In all the sites among HCl-extractable metals (SEM) the Cd concentrations were lower and Zn were highest. Cu, Ni and Pb were intermediate. Vertical distribution of SEM is shown in Table 2 and Figure 3. No significant variation found in Cd concentration with depth in all the four sites. Concentrations of Cu, Ni and Pb at all stations are more or less same at all depths. Zn concentration generally decreased with depth except few peaks in cores DWA2, DWA27 and DWA35.

Table 1. Characteristics of Lake Burragarang sediments

Depth (cm)	Moisture content	pH	Organic matter (%)	Carbonate content (%)
<b>DWA2</b>				
5	68.08	6.0	12.30	3.29
10	61.36	6.5	11.50	2.97
15	57.93	6.7	10.10	2.94
20	52.38	6.6	9.40	2.63
25	49.08	6.6	9.20	2.15
30	46.10	6.8	7.80	2.01
35	43.85	6.7	21.40	5.04
<b>DWA18</b>				
5	63.67	7.8	10.20	1.94
10	53.50	7.5	9.10	1.50
15	50.74	7.7	9.40	1.47
20	48.97	6.9	9.80	1.60
25	48.75	6.5	9.30	1.73
30	49.18	6.5	10.20	1.50
<b>DWA27</b>				
5	73.81	6.1	11.80	2.85
10	64.79	6.3	11.30	2.65
15	61.20	6.7	10.50	2.21
20	52.91	6.7	10.90	2.19
25	52.32	6.9	8.90	1.35
30	54.91	6.8	8.51	1.14
<b>DWA35</b>				
5	69.92	6.9	3.50	1.16
10	59.80	7.3	14.70	14.45
15	61.21	7.5	5.90	4.02
20	57.04	6.9	6.00	4.17
25	57.26	6.9	11.80	7.76
30	47.35	6.8	9.80	2.27
35	45.91	6.8	5.20	1.01

**Table 2. Concentrations of AVS and SEM in sediments of Lake Burragarang**

Depth (cm)	AVS $\mu$ mol/g	Cd $\mu$ mol/g	Cu $\mu$ mol/g	Pb $\mu$ mol/g	Ni $\mu$ mol/g	Zn $\mu$ mol/g	SEM $\mu$ mol/g	SEM/AVS
DWA2								
5	0.50	0.0015	0.075	0.077	0.065	0.34	0.56	1.1
10	0.59	0.0017	0.086	0.087	0.075	0.35	0.60	1.0
15	0.28	0.0017	0.055	0.068	0.06	0.29	0.47	1.7
20	0.45	0.0018	0.071	0.063	0.053	0.28	0.46	1
25	0.29	0.0016	0.046	0.058	0.053	0.21	0.37	1.3
30	0.12	0.0015	0.071	0.053	0.039	0.14	0.30	2.6
35	0.18	nd	0.077	0.045	0.037	0.14	0.30	1.7
DWA18								
5	0.35	0.0018	0.057	0.053	0.065	0.26	0.44	1.2
10	0.38	0.0017	0.035	0.053	0.06	0.31	0.45	1.2
15	0.50	0.0030	0.039	0.063	0.082	0.29	0.48	1
20	0.30	0.0019	0.049	0.042	0.044	0.23	0.37	1.2
25	0.40	0.0016	0.088	0.044	0.056	0.40	0.59	1.5
30	0.13	0.0013	0.069	0.048	0.049	0.31	0.47	3.7
DWA27								
5	0.31	0.0014	0.097	0.087	0.12	0.38	0.69	2.2
10	0.17	0.0011	0.074	0.087	0.107	0.37	0.64	3.7
15	0.18	0.0011	0.066	0.072	0.082	0.28	0.50	2.8
20	0.20	0.0013	0.058	0.072	0.078	0.25	0.45	2.3
25	0.33	0.0012	0.088	0.077	0.077	0.28	0.52	1.6
30	0.26	nd	0.049	0.063	0.058	0.25	0.41	1.6
DWA35								
5	0.21	0.0012	0.072	0.068	0.073	0.28	0.49	2.3
10	0.25	0.0012	0.052	0.063	0.058	0.25	0.42	1.7
15	0.14	0.0013	0.077	0.082	0.072	0.31	0.54	3.9
20	0.10	0.0015	0.047	0.047	0.043	0.18	0.32	3.1
25	0.17	nd	0.077	0.068	0.066	0.28	0.49	2.9
30	0.09	nd	0.036	0.042	0.034	0.18	0.30	3.4
35	0.10	0.0012	0.035	0.042	0.036	0.14	0.25	2.5

nd= Not detected

**Table 3. Correlation coefficient between AVS and organic matter**

Site	Moisture content	pH	Organic matter	Carbonate content
DWA 2	0.800*	-0.654	-0.144	-0.062
DWA 18	0.136	0.589	-0.683	-0.061
DWA 27	0.068	-0.142	-0.278	-0.198
DWA 35	-0.167	0.213	0.419	0.869*

\* Correlation is significant at .05 level (2tailed)

**Table 4. Percentage of SEM-metal and total metal**

Depth (cm)	SEM-Cd	SEM-Cu	SEM-Pb	SEM-Ni	SEM-Zn
	$\Sigma$ SEM	$\Sigma$ SEM	$\Sigma$ SEM	$\Sigma$ SEM	$\Sigma$ SEM
DWA2					
5	0.27	13.39	13.75	11.61	60.71
10	0.28	14.33	14.50	12.50	58.33
15	0.36	11.70	14.47	12.77	61.70
20	0.39	15.43	13.70	11.52	60.87
25	0.43	12.43	15.68	14.32	56.76
30	0.50	23.67	17.67	13.00	46.67
35	0.00	25.67	15.00	12.33	46.67
DWA18					
5	0.41	12.95	12.05	14.77	59.09
10	0.38	7.78	11.78	13.33	68.89
15	0.63	8.13	13.13	17.08	60.42
20	0.51	13.24	11.35	11.89	62.16
25	0.27	14.92	7.46	9.49	67.80
30	0.28	14.68	10.21	10.43	65.96
DWA27					
5	0.20	14.06	12.61	17.39	55.07
10	0.17	11.56	13.59	16.72	57.81
15	0.22	13.20	14.40	16.40	56.00
20	0.29	12.89	16.00	17.33	55.56
25	0.23	16.92	14.81	14.81	53.85
30	0.00	11.95	15.37	14.15	60.98
DWA35					
5	0.24	14.69	13.88	14.90	57.14
10	0.29	12.38	15.00	13.81	59.52
15	0.24	14.26	15.19	13.33	57.41
20	0.47	14.69	14.69	13.44	56.25
25	0.00	15.71	13.88	13.47	57.14
30	0.00	12.00	14.00	11.33	60.00
35	0.48	14.00	16.80	14.40	56.00

SEM-metal concentrations and their percentages to SEM value are presented in Table 4. The concentrations of five acid extracted-metals differed considerably, zinc

accounted for approximately 47– 69% of the total amount of the acid extracted-metals, whereas the contribution of cadmium to SEM was only 0.17- 0.63%.

**Table 5. Guidance on determining metal toxicity to benthic organisms in freshwater sediments (values in mg/kg) [32]**

Metal	Threshold effect level (TEL)	Upper effect threshold (UET)
Cd	0.596	3
Cu	35.7	86
Pb	35	127
Ni	18	43
Zn	123.1	520

The SEM/AVS ratio presented in Table 2 showed that these simultaneously extracted metals at all stations were higher than AVS and their ratio was found greater than 1, which indicates that available AVS is not a major metal binding component for Lake Burragarang sediments and possibly contained metals potentially bioavailable to benthic organisms. However, the levels of AVS concentrations measured in the Lake Burragarang sediments are low compared to values reported in the literature for fresh water sediments [27]. AVS concentration depends on season and depth. Many researchers observed variation in AVS levels with season [27,28,29,30]. Major decrease occurred in the winter because in colder temperatures, FeS formation rates were lower and a smaller supply of FeS-rich particles was brought up from below by bioturbation [28].

For the present study, sediments for SEM and AVS were collected for analysis in winter season and hence the low level of AVS was found. Low AVS concentrations indicate that most metals are bound by sediment constituents other than AVS [9]. A study conducted by Lawrence Berkeley National Laboratory (LBNL) also had sites with SEM-AVS values greater than one due to relatively low AVS values and not necessarily high concentrations of metals. No toxicity to benthic organisms was observed from these LBNL sites [29]. Other

constituents in the sediment, such as iron and manganese oxides and organic matter, may have decreased the bioavailability of heavy metals [4]. The unbound metals toxicity to benthic organisms can be explained by analyzing individual SEM concentrations according to their threshold effects level (TEL) and upper effects threshold (UET) levels (Table 5). All the locations had individual SEM concentrations lower than their TEL. Even though these investigated metals were bioavailable in the sediment their individual metal concentrations are not expected to be toxic to benthic organisms.

### 4. Conclusion

The results showed that these SEMs at all stations were higher than AVS and their ratio was found greater than 1, which indicates that available AVS is not sufficient to bind with the extracted metals for Lake Burragarang sediments and possibly contained metals potentially bioavailable to benthic organisms, however, AVS values in this study are low compared to values reported in the literature for fresh water sediments so SEM/AVS ratio could be high owing to relatively low AVS values and not due to high concentrations of metals. Further, the seasonal cycle of SEM and AVS can alter the potential toxicity criteria of sediments. The present study was done during winter period. As reported earlier significant decrease occurred in the winter period because microbial activity reduced in colder temperature. In other words sediment that is non-toxic during the period of high AVS (i.e in

summer) can become potentially toxic during periods of low AVS (i.e in winter) [31]. In the current study even though these investigated metals were bioavailable in the sediment their individual metal concentrations are not expected to be toxic to benthic organisms as all locations had SEM concentrations lower than their threshold effects level (TEL). However, slight increase in SEM above TEL will be detrimental for aquatic system as available AVS in sediment of Lake Burragarang is not sufficient to bind with the extracted metals. Further, continuous and constant monitoring of Lake Burragarang sediment for SEM and AVS is recommended to protect the aquatic system from the toxic effect of free metals.

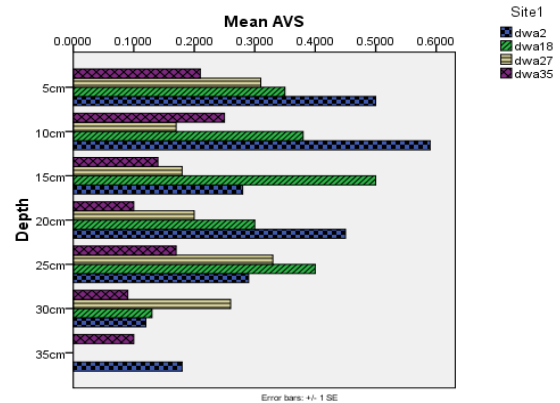


Figure 2. Vertical distribution of AVS

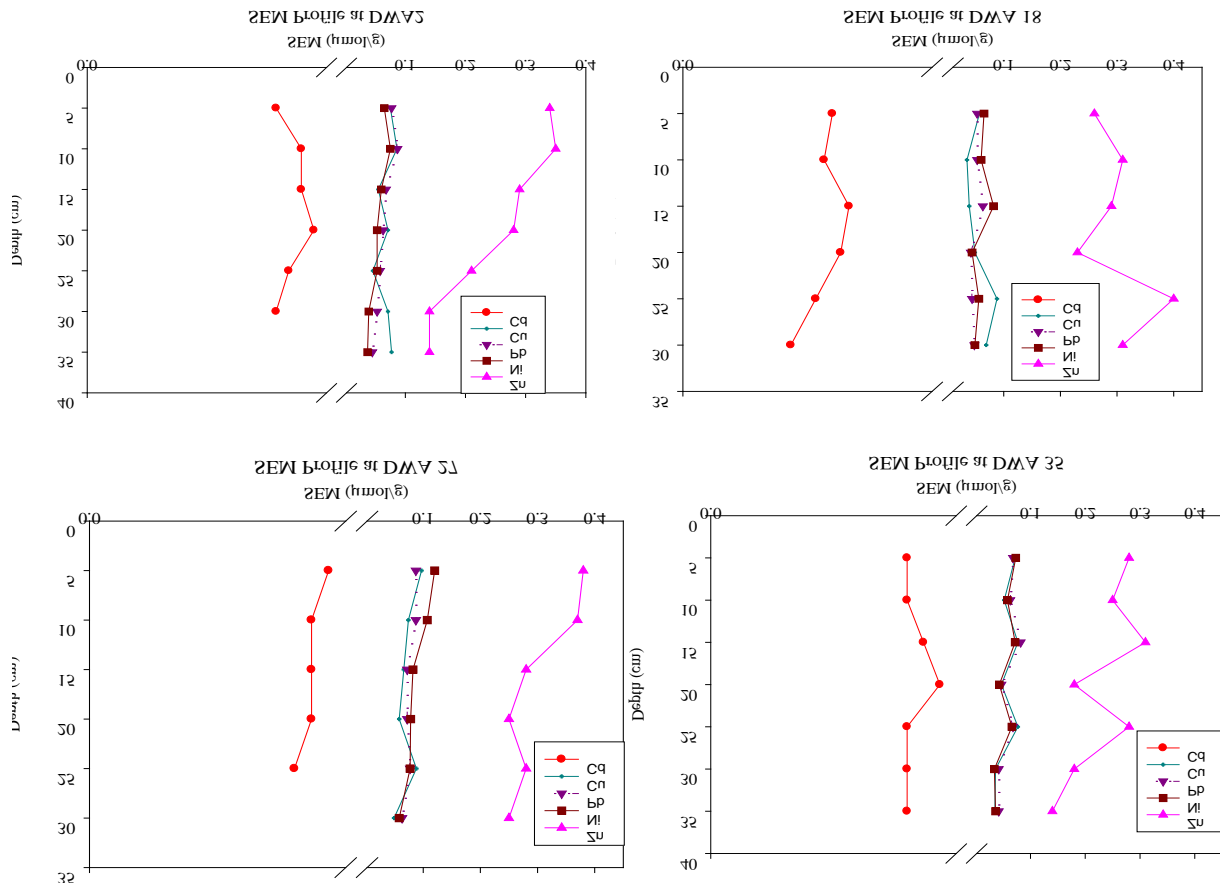


Figure 3. Vertical distribution of SEM

## Acknowledgements

The authors are grateful to Dr. Honway Luie and Dr. Michael Wu of Australian Government Analytical Laboratories, Sydney, Australia, for providing the standard reference samples and sediment samples analysis for metals concentration. The financial assistance from SEEWRT (Sustainability in Ecological Engineering and Resources Technology) research group, University of Western Sydney, Australia is greatly acknowledged. One of the authors would like to express thanks and appreciation to the Chancellor, Pro Chancellor and Vice Chancellor of Shri Ramswaroop Memorial University, India for their moral support and encouragement.

## Statement of Competing Interests

Authors have no competing interests

## References

- [1] Yu KC, Tsai LJ, Chen SH, Ho ST. Chemical Binding of Heavy Metals in Anoxic River Sediments, *Water Research*, 35, 4086-4094, 2001.
- [2] Ankley GT, Di Toro DM, Hansen DJ. Technical basis and proposal for deriving sediment quality criteria for metals, *Environmental Toxicology and Chemistry*, 15: 2056-2066, 1996.
- [3] Cooper DC, Morse JW. Extractability of metal sulfide minerals in acidic solutions: application to environmental studies of trace metal contamination within anoxic sediments, *Environmental Science & Technology*, 32, 1076-1078, 1998.
- [4] Di Toro DM, Mahony JD, Hansen DJ. Toxicity of cadmium in sediments: role of acid volatile sulphide, *Environmental Toxicology and Chemistry*, 9, 1487-1502, 1990.
- [5] Di Toro DM, Mahony JD, Hansen DJ, Scott KJ, Carlson AR, Ankley GT. Acid volatile sulfide predicts the acute toxicity of cadmium and nickel in sediments, *Environmental Science & Technology*, 26, 96-101, 1992.
- [6] Buykx SEJ, van den Hoop MAGT, Loch JPG. Dissolution Kinetics of Heavy Metals in Dutch Carbonate-and Sulfide-Rich Freshwater Sediments, *J. Environ. Qual.*, 31, 573-580, 2002.
- [7] Van den Hoop MAGT, den Hollander HA, Kerdijk HN. Spatial and seasonal variations of acid volatile sulfide (AVS) and simultaneously extracted metals (SEM) in Dutch marine and freshwater sediments, *Chemosphere*, 35, 2307-2316, 1997.
- [8] Jingchun L, Chongling Y, Spencer KL, Ruifeng Z, Haoliang L. The distribution of acid-volatile sulfide and simultaneously extracted metals in sediments from a mangrove forest and adjacent mudflat in Zhangjiang Estuary, China, *Marine Pollution Bulletin*, 60, 1209-1216, 2010.
- [9] Allen HE, Fu G, Deng B. Analysis of acid volatile sulfide (AVS) and simultaneously extracted metals (SEM) for the estimation of potential toxicity in aquatic sediments. *Environmental Toxicology and Chemistry*, 12, 1441-1453, 1993.
- [10] Huerta-Diaz M, Tessier A, Carignan R. Geochemistry of trace metals associated with reduced sulfur in freshwater sediments. *Applied Geochemistry*, 13, 212-233, 1998.
- [11] Batley GE. Collection, preparation, and storage of samples for speciation analysis, *In Trace Element Speciation: Analytical Methods and Problems*, ed. G. E. Bailey: CRC Press, Boca Raton, Florida, 1989.
- [12] Dean WE. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods, *Journal of Sedimentary Research*, 44, 242-48, 1974.
- [13] Kunz MJ, F. S. Anselmetti, A. Wüest, B. Wehrli, A. Vollenweider, S. Thüning, and D. B. Senn Sediment accumulation and carbon, nitrogen, and phosphorus deposition in the large tropical reservoir Lake Kariba (Zambia/Zimbabwe), *J. Geophys. Res.*, 116, 2011.
- [14] Al-Rousan S, Rasheed M, Al-Horani F, Manasrah R. Geochemical and textural properties of carbonate and terrigenous sediments along the Jordanian coast of the Gulf of Aqaba, *Journal of Oceanography*, 62, 839-849, 2006.
- [15] Alves JPH, Passos EA, Garcia CAB. Metals and Acid Volatile Sulfide in Sediment Cores from the Sergipe River Estuary, Northeast, Brazil, *J. Braz. Chem. Soc.*, 18 (4), 748-758, 2007.
- [16] Hansen DJ, Berry WJ, Mahony JD, Boothman WS, Di Toro DM, Robson DL, et al. Predicting the toxicity of metal contaminated field sediments using interstitial concentration of metals and acid-volatile sulfide normalizations, *Environmental Toxicology and Chemistry* 15, 2080-2094, 1996.
- [17] Howard DE, Evans, R.D. Acid-volatile sulfide (AVS) in a seasonally anoxic mesotrophic lake: seasonal and spatial changes in sediment AVS, *Environmental Toxicology and Chemistry*, 12, 1051-1057, 1993.
- [18] Leonard E. N. Agatha. Evaluation of metals in marine and freshwater surficial sediments from the Environmental Monitoring and Assessment Program relative to proposed sediment quality criteria for metals, *Environmental Toxicology and Chemistry*, 15, 2221-2231, 1996.
- [19] Liber K, Call DJ, Markee TP, Schmude KL, Balcer MDW, F. W., Ankley GT. Effects of acid-volatile sulfide on zinc bioavailability and toxicity to benthic macro invertebrates: a spiked-sediment field experiment, *Environmental Toxicology and Chemistry*, 15, 2113-2125, 1996.
- [20] Oehm NJ, Luben, T.J., Ostrofsky, M.L., Spatial distribution of acid volatile sulfur in the sediments of Canadohta Lake PA, *Hydrobiologia*, 345, 79-85, 1997.
- [21] Peterson GS, Ankley GT, Hoke RA. Effect of bioturbation on metal-sulfide oxidation in surficial freshwater sediments, *Environmental Toxicology and Chemistry*, 15, 2147-2155, 1996.
- [22] Fang T, Li X, Zhang G. Acid volatile sulfide and simultaneously extracted metals in the sediment cores of the Pearl River Estuary, South China, *Ecotoxicology and Environmental Safety*, 61, 420-431, 2005.
- [23] Jeroen WMW, Jack JM, Peter MJH, Michael EBT, Carlo HRH. Sulfur and iron speciation in surface sediments along the northwestern margin of the Black Sea, *Marine Chemistry*, 74, 261-278, 2001.
- [24] Song YS, Mu`ller G. *Sediment-water interactions in anoxic freshwater sediments-mobility of heavy metals and nutrients*. Springer, Berlin. 1999.
- [25] Nedwell DD, Abram, J.W. Bacterial sulfate reduction in relation to sulfur geo-chemistry in two contrasting areas of salt marsh sediment, *Estuary Coastal Marine Science*, 6, 341-351, 1978.
- [26] Matisoff G, Holdren GR. A model for sulfur accumulation in soft water Lake sediments, *Water Resour. Res.*, 31, 1751-1760, 1995.
- [27] Machesky ML, Holm TR, Shackleford DB. *Concentrations and Potential Toxicity of Metals and Ammonia in Peoria Lake Sediments and Pore Waters*. Waste Management and Research Center, Illinois Department of Natural Resources, Champaign, Illinois, 2004.
- [28] Aller RC. *The Influence of Macrobenthos on Chemical Diagenesis of Marine Sediment*. Yale University, New Haven, CT., 1977.
- [29] Grabowski LA, Houppis JJJ, Woods WI, Johnson KA. Seasonal bioavailability of sediment-associated heavy metals along the Mississippi river floodplain, *Chemosphere*, 45: 643-651, 2001b.
- [30] Morse J, Rickard D. Chemical Dynamics of Sedimentary Acid Volatile Sulfide, *Environmental Science and Technology*, 38, 131A-136A, 2004.
- [31] Di Toro DM, Mahony JD, Hansen DJ, Berry WJ. A model of the oxidation of iron and cadmium sulfide in sediments. *Environmental Toxicology and Chemistry*, 15, 2168-2186, 1996.
- [32] Grabowski LA, Houppis JJJ, Woods WI, Johnson KA. Seasonal bioavailability of sediment-associated heavy metals along the Mississippi river floodplain, *Chemosphere*, 45, 643-65, 2001a.